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MAGNETO-SURFACE EXPERIMENTS ON GERMANIUM AT LOW TEMPERATURES

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Abstract: The conductivity and the Hall coefficient have been measured on several high resistivity p-type and n-type germanium samples at reduced temperatures as function of the charge induced by the field effect. The results are compared with the three carrier theoretical expressions of Petritz, using surface mobilities based on the theory of diffuse surface scattering. Comparison is also made with theoretical expressions when surface mobilities are taken equal to bulk mobilities of corresponding carriers. Calculations based on diffuse surface scattering agree fairly well with the experimental data for majority carriers in accumulation and depletion layers. For minority carriers in the inversion layers experimental and theoretical data disagree for both specular and diffuse surface scattering models.

1. *Introduction*

The mobility of carriers confined to the semiconductor surface region differs from their bulk mobility as these carriers suffer additional collisions with the surface. A reduction of the mobility at the surface was predicted by the theory of Schrieffer[1] on the assumption of diffuse surface scattering. Subsequent studies by Greene *et al.*[2], Grover *et al.*[3] and Goldstein *et al*[4] led to expressions for surface mobility of carriers as function of the surface potential over the whole range of practical interest.

First experimental test of the Schrieffer's theory was performed by Zemel and Petritz[5, 6] on near intrinsic germanium at room temperature, using expressions, derived by Petritz[7], for Hall and magnetoresistance coefficients of a semiconductor with surface carrier excesses. They confirmed the existence of the predicted mobility reduction for surface carriers and indicated the importance of light holes in semiconductor surface transport. Later Albers and Thomas[8] and Albers[9] have found diffuse scattering from their magnetoresistance measurements on n-type germanium. While all these measurements were made using gas ambients to modulate surface space charge region, Sytenko and Koshel[10] used field effect in similar experiments. One of us[11] using field effect on high resistivity p-type germanium in the vicinity of room temperature, obtained substantial changes of conductivity and of Hall coefficient, which agreed with the diffuse surface scattering model for holes but less for electrons. Scott and Zemel[12] measured the extrinsic n-type germanium at liquid nitrogen temperature and found a strong degree of diffuse scattering for electrons. Recently Rzhanov *et al.*[13] performed combined field effect and Hall effect measurements on very high purity epitaxial layers of germanium at reduced temperatures. They showed that the scattering is totally diffuse on a specimen surface prepared by polishing and etching, for both electrons and holes, and to a large extent specular on the natural growth surface for holes.

Contrary to these galvanomagnetic surface studies, which indicate mostly diffuse surface scattering measurements of the field effect have been contradictory. Millea and Hall[14] on germanium and silicon and Many *et al.*[15] on germanium found evidence for some specularity on n-type accumulation layers.

In this work we have made simultaneous measurements of conductivity and Hall coefficient changes at reduced temperatures on both p- and n-type high resistivity germanium samples using field effect to modulate surface carrier excesses.

2. *Experimental procedure and results*

Specimens have been prepared from single crystal slices in the form of rectangular slabs, with eccentrically placed side arms, using an ultrasonic cutter. Specimen surfaces were lapped to a thickness of the order of 0.2 mm. After washing in an ultrasonic cleaning bath, contacts were soldered on both sides of the specimen and current and potential leads were attached, suitably masked with a protective paint. Specimens were etched in a heated CP-4A solution to a thickness of 0.1 mm, washed in a stream of deionized water and dried with warm air. Measured capacitance of the specimen and a brass electrode with a thin »Mylar« spacer was of the order of 80 % of the geometrical capacitance. The jig with a specimen was mounted in a glass chamber immersed in a Dewar flask with liquid nitrogen and fitted between pole pieces of an electromagnet. The sample chamber was maintained at a pressure of 10^{-3} torr. Specimens were supplied with a constant current in the μA range. Magnetic field was cycled in regular intervals while the specimen was subjected to a DC field effect. Signal from the side arms was fed via a bucking off voltage source to the vibrating reed electrometer and recorded. One such recording with relaxation transients omitted, is reproduced in Fig. 1 in which the conductivity is plotted versus voltage on the electrode, for the magnetic field turned on, off and reversed.

Considerable time was spent in attempts to achieve specimen contacts, ohmic to both majority and minority carriers. Suggestion made by Litovchenko[16, 17] was adopted and contacts were prepared by soldering one set, containing impurities corresponding to minority carriers on the face adjacent to the field electrode, and a second set containing the opposite type of impu-

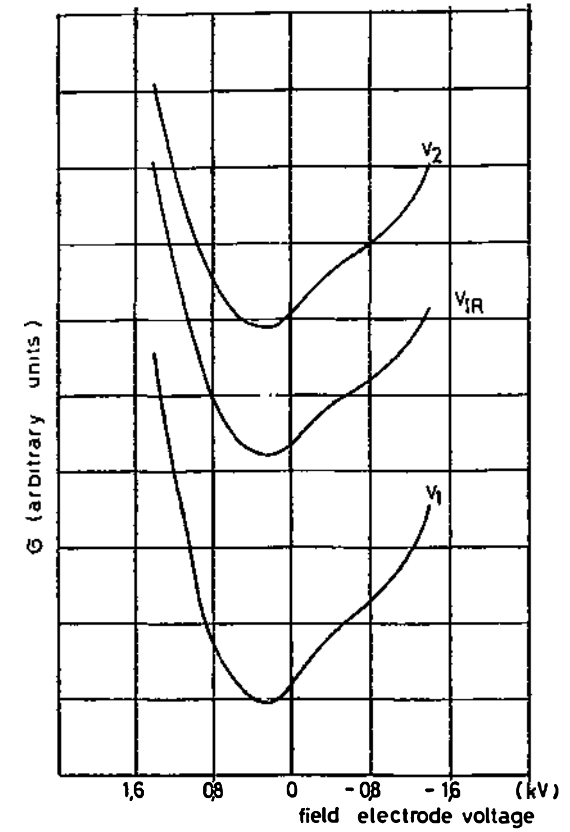
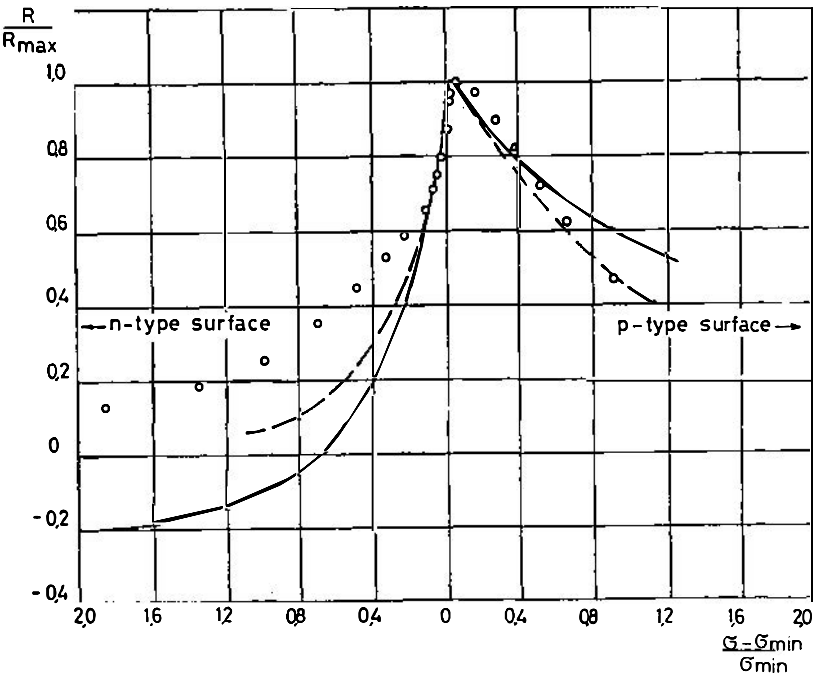


Fig. 1. Recording of the signals appearing at the side arms during the field effect experiment with an n-type specimen ($N_d - N_a = 1.13 \cdot 10^{13}$ cm^{-3}) at $T = 173.5$ K. V_{IR} is the potential drop without the magnetic field. V_1 and V_2 are the signals composed of the V_{IR}, Hall voltage and magnetoresistance voltage for two directions of the magnetic field.

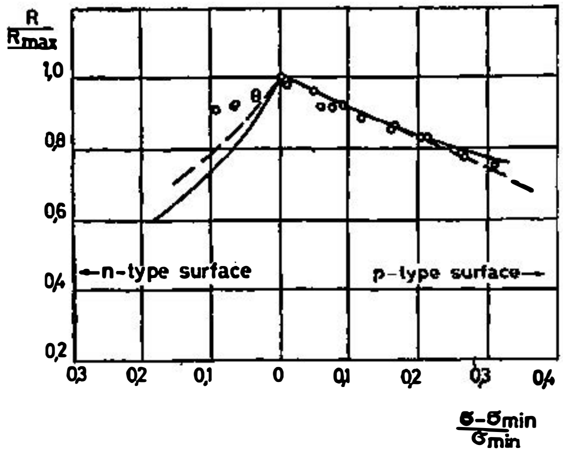
rities, to the opposite face. This procedure helped in obtaining conductivity minimum at reduced temperatures. In some cases the conductivity had a maximum on the minority carrier side and the Hall coefficient increased monotonously. These measurements have been rejected.

All specimens had their major faces oriented nearly in (111) plane. Magnetic field strength was of the order of 2.5 kOe. Magnetic field dependence has not been investigated. For all specimens but one, only one field electrode was employed.

Experimental results denoted with circles have been plotted as normalized values of the Hall coefficient versus the fractional change of conductivity with respect to the minimum. Data for one p-type specimen are shown in



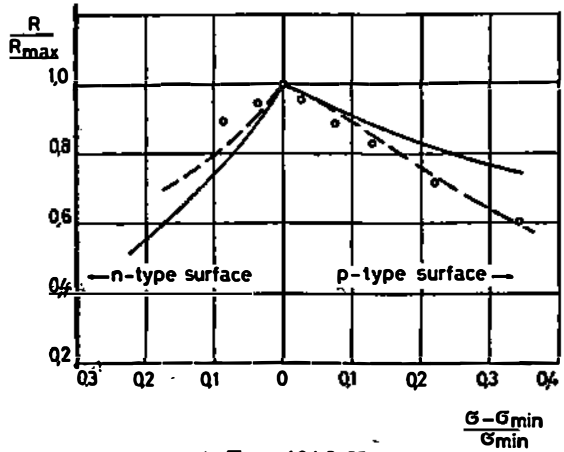
a) T = 275 K



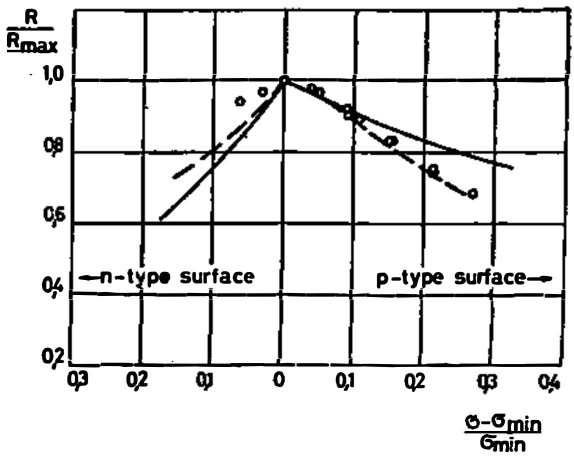
b) T = 151 K

Fig. 2. Normalized values of the Hall coefficient R/R_{max} versus the fractional change of conductivity with respect to the minimum $(\sigma - \sigma_{min})/\sigma_{min}$. Circles denote experimental values obtained for a p-type specimen ($N_a - N_d = 1.90 \cdot 10^{13}$ cm^{-3}). Calculations are represented by full and broken lines corresponding to specular and diffuse surface scattering respectively.

Figs. 2a) and 2b). Substantial changes of the measured quantities have been obtained at 275 K [Fig. 2a)] while reproducibility of the results was good for both directions of the field effect cycle. Data for the same specimen at 151 K are shown on Fig. 2b). At this temperature considerably less changes have been obtained. Reducing the temperature stronger inversion has not been reached because of the bulk Fermi level shift towards the majority carrier band. Two field electrodes have been employed in this case. Figs.



a) T = 184.5 K



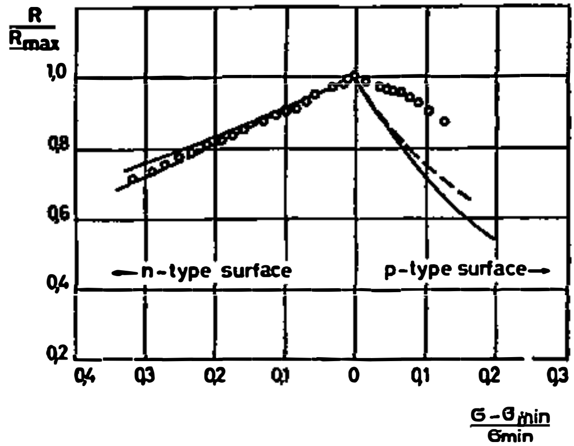
b) T = 155 K

Fig. 3. R/R_{max} versus $(\sigma - \sigma_{min})/\sigma_{min}$ for a p-type specimen ($N_a - N_d = 4.26 \cdot 10^{13}$ cm^{-3})

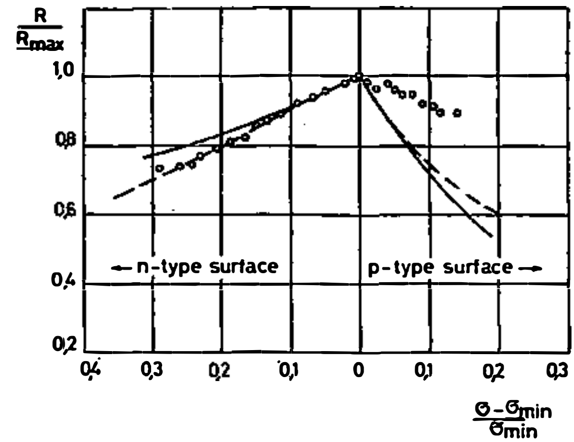
3 a) and 3 b) show experimental results for another p-type specimen at two reduced temperatures. The results for an n-type specimen are shown on Figs. 4a) and 4b). The overall changes of the Hall coefficient and the conductivity are nearly the same as for the p-type specimens for the same temperature range. Measurements at temperatures lower than 150 K have not been made.

3. *Analysis and discussion of the results*

The conductivity change $\sigma - \sigma_b$ and the Hall coefficient R were calculated as functions of the surface potential u_s using the three carriers formulae and surface carrier excesses calculated from the results of Kingston and Neustadter[18], and Frankl[19]. Terms involving the bulk carriers and the correlation terms were neglected. Lattice scattering was assumed in the bulk while for μ_n and μ_p empirical formulae, given by Morin and Maita[20], were used. For the light holes parameters the values $r_{32} = 2.25 \cdot 10^{-2}$ and $b_{32} = 7.5$ were used, as given by Willardson *et al.*[21]. Eliminating u_s one obtains unique dependence between the Hall coefficient and the fractional change of conductivity with respect to the minimum.



a) $T = 190$ K



b) $T = 173.5$ K

Fig. 4. R/R_{max} versus $(\sigma - \sigma_{min})/\sigma_{min}$ for a n-type specimen $(N_a - N_d = 1.13 \cdot 10^{13}\ \mathrm{cm}^{-3})$

In first calculations all mobilities are set equal to their bulk values. In order to compare experimental data with the calculated ones we normalize the values of the Hall coefficient and plot R/R_{max} versus $(\sigma - \sigma_{min})/\sigma_{min}$. In all cases theoretical curves deviate from the experimental points for accumulation as well as inversion layers.

Next, the mobility reduction is introduced and the above quantities are recalculated using the results[3,4] for totally diffuse surface scattering. Following Zemel and Petritz[5] we assume that the light and heavy hole mobilities are reduced by the same fraction for a given surface potential, and that the effective Hall mobilities are reduced in the same proportion as the effective conductivity mobilities. Broken lines on the corresponding figures represent the results of these calculations. Fairly good fit is obtained with mobility reduction for majority carriers for both p- and n-type specimens at all temperatures, indicating the diffuse surface scattering in accumulation layers. For the inversion layers, however, there is still appreciable difference between the calculated and experimental values although certain improvement as compared with the calculations using bulk mobilities is evident. Unfortunately, conditions of the experiment did not allow a stronger inversion, which would enable us to obtain experimental values for minority carrier mobilities.

Considering the results for inversion layers, one can speculate about some possible explanations for the observed differences between the experimental and the calculated values. One possibility suggested by Albers[9] might be an unknovn additive contribution to the measured values of the Hall voltage due to the low surface recombination velocity of etched surfaces. This contribution should become negligible for higher values of surface recombination velocity. Since surface recombination velocity is higher at temperatures below 200 K, for at least an order of magnitude or more than at room temperature, one can assume that it does not affect our Hall effect data significantly.

Leaving aside the experimental uncertainties one could try to use different values for some parameters involved in the calculations. This would mean the use of different values for surface mobilities, different ratios of the surface Hall coefficient to conductivity mobilities, and some other parameters for light holes. As far as the surface mobility is concerned, different scattering mechanisms have been proposed recently in connection with the study on the silicon MOS structures such as influences of the ionized impurity scattering[22] and of the misfit dislocations[23] on the carrier transport in surface channels. Before trying to compare the experimental data for inversion layers with these models, additional measurements are needed, with different surface treatments, and higher inversions, as well as studies of magnetic field and orientation dependence. Such measurements might shed some more light on the problem of carrier transport in inversion layers of germanium.

References

1) J. R. Schrieffer, Phys. Rev. **97** (1955) 641;
2) R. F. Greene, D. R. Frankl and J. Zemel, Phys. Rev. **118** (1960) 967;
3) N. B. Grover, Y. Goldstein and A. Many, J. Appl. Phys. **32** (1961) 2538;
4) Y. Goldstein, N. B. Grover, A Manny and R. F. Greene, J. Appl. Phys. **32** (1961) 2540;
5) J. N. Zemel and R. L. Petritz, Phys. Rev. **110** (1958) 1263;
6) J. N. Zemel and R. L. Petritz, J. Phys. Chem. Solids 8 (1959) 102;
7) R. L. Petritz, Phys. Rev. **110** (1958) 1254;
8) W. A. Albers, Jr. and J. E. Thomas, Jr., J. Phys. Chem. Solids **14** (1960) 181;
9) W. A. Albers, Jr., J. Phys. Chem. Solids **23** (1962) 1249;
10) T. N. Sytenko and O. N. Koshel, Fiz. Tver. Tela **3** (1961) 1079;
11) D. Čajkovski, Ph. D. Thesis, University of Zagreb (1964), unpublished;
12) E. J. Scott and J. N. Zemel, Bull. Am. Phys. Soc., Ser. II 8 (1963) 295;
13) A. V. Rzhanov, V. P. Migal and N. N. Migal, Fiz. i Tekh. Poluprovodnikov **3** (1969) 231;
14) M. F. Millea and T. C. Hall, Phys. Rev. Letters **1** (1958) 276;
15) A. Many, N. B. Grover, Y. Goldstein and E. Harnik, J. Phys. Chem. Solids **14** (1960) 186;
16) V. G. Litovchenko, A. P. Gorban and V. P. Kovbasiuk, Ukrayin, fiz. Zhur. **10** (1965) 287;
17) V. G. Litovchenko, private communication;
18) R. H. Kingston and S. F. Neustadter, J. Appl. Phys. **26** (1955) 718;
19) D. R. Frankl, J. Appl. Phys. **31** (1960) 1752;
20) F. J. Morin and J. P. Maita, Phys. Rev. **94** (1954) 1525;
21) R. K. Willardson, T. C. Harman and A. C. Beer, Phys. Rev. **96** (1954) 1525;
22) F. Berz, Solid-St. Electronics **13** (1970) 903;
23) G. F. Neumark, Phys. Rev. **B1** (1970) 2613.

POVRŠINSKI MAGNETSKI EKSPERIMENTI NA GERMANIJU KOD NISKIH TEMPERATURA

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Sadržaj

Rad opisuje i daje rezultate kombiniranih mjerenja promjena električne vodljivosti i Hallovog koeficijenta na visokoomskim primjercima germanija p- i n-tipa koja su vršena radi proučavanja procesa površinskog raspršenja nosilaca električnih naboja kod niskih temperatura. Promjene električne vodljivosti i Hallovog koeficijenta ostvarivane su primjenom efekta polja.

Rezultati mjerenja uspoređuju se s vrijednostima izračunatim na osnovu Petritzove teorije površinskih galvanomagnetskih koeficijenata. Određivanje teorijskih vrijednosti je izvršeno primjenom relacija za tri vrste nosilaca električnih naboja. Za pokretljivosti površinskih viškova nosilaca najprije su uzete vrijednosti unutrašnjih pokretljivosti, a zatim površinske pokretljivosti koje daje teorija potpuno difuznog površinskog raspršenja.

I kod p-tipa i kod n-tipa germanija utvrđeno je da za glavne nosioce postoji dobro podudaranje rezultata mjerenja i teorijskih vrijednosti i to onda, kad su ove posljednje određene uzimajući u obzir smanjenje površinske pokretljivosti koje uzrokuje difuzno raspršenje.

Za sporedne nosioce rezultati mjerenja se nisu slagali s teorijskim vrijednostima kod oba tipa germanija. Ukazuje se na moguće uzroke toga neslaganja i razmatraju se mogućnosti za dodatne eksperimente koji bi dali bolji uvid u mehanizam površinskog raspršenja sporednih nosilaca u germaniju.